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# Analysis of steel bolted double angle connections at elevated temperatures

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ABSTRACT

Double angle connections are one of the common simple beam-end framing connections used in steel structures, but current building standards do not provide much guidance on how to design these connections for fire. Development of such design methodologies is particularly hindered by the lack of adequate understanding of the strength and deformation capacities of double angle connections in fire. To address this issue, this paper presents key results of a computational study of the influence of fire temperatures on steel double angle connections. Computational models for double angle connections are developed in Abaqus and evaluated against experimental data from the literature at both ambient and elevated temperatures. An extensive study is then conducted to investigate different parameters that impact the behavior of double angle connection assemblies during a fire. A comparison is also made between the performances of double angle and shear tab connections at elevated temperatures. Results obtained in this study show that the main factors impacting the behavior of double angle connections at elevated temperatures are load ratio, initial cooling temperature, location of the double angle with respect to the beam neutral axis, and the gap distance. In addition, double angle connections showed better performance at elevated temperatures when compared to shear tab connections.



## 1. Introduction

Connections have a crucial role in maintaining the overall stability of steel structures by providing continuity of load paths between structural elements. During a fire event, connection components can undergo significant loss of strength and stiffness. Large axial forces are also developed in connections and beams as a result of restraints to thermal displacements [1]. These axial forces are initially compressive when beams expand during the initial heating stage of a fire. As the temperature of the structure increases, these axial forces can become tensile as beams begin to sag and catenary action develops. Additional axial tensile forces are developed as deflected beams contract during the cooling stage of a fire [2,3]. To accommodate large beam deflections, steel connections are therefore subjected to significant rotation demands in fire. These large deformation and force demands combined with loss of strength can potentially result in the failure of connections during and after a fire.

Double angle connections, which are sometimes also called web cleat connections, are commonly used to connect beams to columns in steel gravity framing systems. Double angle connections are normally idealized as pinned connections and are typically designed for shear forces only at ambient temperature. Despite this idealization, double angle connections have been shown to possess flexural resistance, large rotational ductility and tying capacity at ambient temperature [4,5]. However, as discussed above, the connection force and deformation demands in fire are significantly different than those at ambient temperature. In order to take advantage of the inherent capacities of double angle connections and to account for them in fire design, it is necessary to better understand the force and deformation demands on double angle connections in fire, and to characterize the strength and deformation capacity of these connections at elevated temperatures.

In recent years, several researchers have studied the behavior of double angle connections at elevated temperatures. For instance, Liu et al. [2] observed in full-scale experiments that the axial restraint provided by double angle connections enhanced the beam performance in fire by allowing the formation of catenary action. Yu et al. [6,7] investigated the performance of double angle connections in fire, both experimentally and computationally, and showed the connections exhibit very good rotational ductility. In addition, Selamet and Garlock [8] compared the behavior of different types of partially restrained steel connections (shear tab,

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single angle, and double angle) in fire using finite element analysis and showed that double angle connections exhibited the most ductile behavior. They also showed that the rate of heating and cooling during a fire could affect the beam stress distribution, peak temperatures, and peak displacements but not the peak axial force [9]. More recently, Pakala et al. [10], and Kodur et al. [11] conducted experimental and computational investigations aiming at understanding the effect of the load level, fire scenario and composite action of the steel-concrete beam/slab assembly on the behavior of double angle connections during a fire. Pakala and Kodur [12,13] further conducted a parametric study using finite element modeling to analyze the effects of several key parameters and connection details on the behavior of double angle connections in fire. The considered parameters are bolt grade, edge-distance, fire scenarios, high-temperature bolt properties, type of bolt-holes, slenderness of beam web, and thermal gradient over the beam cross section.

Despite the above-cited research efforts, large gaps still exist in understanding the overall response of double angle connections exposed to fire. For instance, the governing failure modes of double angle connections at elevated temperatures are not adequately investigated. Furthermore, the fire-imposed axial force demands on beams and connections are not accurately characterized. Finally, current design practice normally treats connections as isolated "pins" at the beam ends. This idealization, while useful at ambient temperature, is not sufficient to characterize the actual stiffness of the connection, which in turn, has a large impact on the forces and deformations induced at a connection in fire. Research is needed to develop practical methods that can consider the effect of thermally-induced forces on the beam-end connections exposed to fire.

To address the above-mentioned shortcomings, in this paper, finite element models of double angle connections at ambient and elevated temperatures are developed and validated against results from corresponding experiments conducted at the University of Sheffield [6,14]. Finite element models of a connection assembly are further generated and used to conduct an extensive parametric study to identify the key parameters that affect the behavior of double angle connections during the heating and cooling stages of a fire. Finally, a comparison of the performance of the shear tab and double angle connections in a fire is performed.

## 2. Finite element model of isolated double angle connections at elevated temperatures

In this section, the finite element model of the double angle connection is described. Results from the finite element model of the double angle connection are compared with those obtained in the experimental program at the University of Sheffield [6,14]. Table 1 summarizes the connection tests from the University of Sheffield that are reproduced in this paper.

### 2.1. Development of the finite element model

Important features of the finite element model of the double angle connection along with analysis procedure are described below. For evaluation purposes, the finite element model of the double angle connection is developed to replicate the specimens used in the experimental program at the University of Sheffield [6,14]. An overall view of the model is shown in Fig. 1. The finite element model of the connection was developed in Abaqus [15].

**Table 1**
Summary of the simulation reproduced from the Sheffield University tests.

| Temperature (°C) | Initial angle inclination (deg) |
|---|---|
| **20** | 35 |
| **450** | 35 |
| **550** | 35 |
| **650** | 35 |

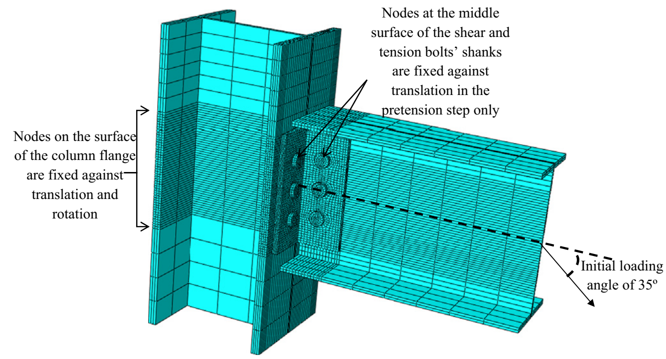


**Fig. 1.** Connection details in finite element model.

#### 2.1.1. Geometry of connection components

The bolted double angle connection specimen used in the analysis consists of two 2L 90 × 90 × 8 mm angles, as used in the experiment. The two angles connect a UC 254 × 89 column to a UB 305 × 40 beam. Bolts of 19 mm diameter are used for both the tension and shear bolts. Details of the connection configuration can be found in [6,14].

#### 2.1.2. Geometric and force boundary conditions

The model is loaded in two steps. The first step applies a pretension force in the tension and shear bolts. The bolt pre-tensioning is modeled by applying a body force in the bolts equivalent to the minimum required pretension force specified in the AISC Specification [16]. The second step applies load monotonically to the connection. Force control is used in the analysis where a concentrated force is applied on the tip of the beam at an initial angle of 35 ° with respect to the beam centerline as shown in Fig. 1. Note that the loading angle is varied throughout the analysis in accordance with the experimental program performed at the University of Sheffield [6,14] to produce a varying tensile and shear force on the connection.

Throughout the analysis, boundary conditions are applied on different elements of the double angle connection as shown in Fig. 1. During the pretensioning step, the shear and tension bolts are restrained against any translation to ensure contact between the bolt head and nut, and steel material. The angles are also restrained from translation to ensure they maintain their contact with the shear bolts, the tension bolts, the beam web and the column flange. In addition, the top and bottom face of the column are restrained against translation and rotation. During the second loading step, only the boundary conditions on the top and bottom face of the column are kept active.

#### 2.1.3. Material properties

An idealized bilinear model is used for the steel materials. The ambient-temperature mechanical properties used for the beam are: the yield stress $F_y$ = 52 ksi (356 MPa), and the ultimate stress $F_u$ = 73 ksi (502 MPa) which are in accordance with [6]. For the double angle, the material model specified in [6] with $F_y$ = 50 ksi (350 MPa) and $F_u$ = 66 ksi (455 MPa) is incorporated in the finite element model. For the column, the ambient-temperature mechanical properties used are S355 as specified in [14]. For the structural bolts, an elastic-perfectly plastic material model is used.